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INVESTIGATION OF ULTRASONIC WELDING OF REFRACTORY METALS AND ALLOYS

September 1963

Prepared under Navy Bureau of Naval Weapons
Contract No. NOw 63-0125-c

Bimonthly Progress Report No. 6
16 June 1963 through 15 August 1963

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WEST CHESTER, PENNSYLVANIA

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ABSTRACT

Ultrasonic welds in Inconel X-750 and in molybdenum-0.5% titanium alloy produced with power-force programming showed significantly higher strengths than those made with conventional power and force application. Metallographic examination of the molybdenum alloy welds revealed superior bonding.

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Mo,Cb,W,Al,NiB,SS 53640 Card 2/2

INVESTIGATION OF ULTRASONIC WELDING OF REFRACTORY METALS AND ALLOYS

This program on ultrasonic welding of refractory metals is concerned with the application of Power-Force Programming (PFP) during the weld interval to improve weld quality and reproducibility in refractory metals.

Earlier effort involved the development of PFP equipment whereby both power and force were varied in ten increments stepwise during a weld interval. Components of the equipment were assembled on a laboratory-type 4-kilowatt ultrasonic spot-type welder, and refinements have been progressively made to provide better response and more reliable operation of the systems.

~~Since~~ work ~~under an~~ earlier ~~contract~~ ~~(1)*~~ ~~had~~ indicated that good welds could not be accomplished in materials of inferior quality, effort was directed toward procurement of higher quality refractory metals. The metals for this program include molybdenum-0.5% titanium alloy obtained from the General Electric Company, B-66 niobium (columbium) alloy from Westinghouse Electric Corporation, and tungsten from Fansteel Metallurgical Company.

Scouting investigations with welding selected gages of 2024-T3 aluminum alloy, Inconel X-750, and Type 304 stainless steel indicated that power-force programming has a significant beneficial effect on weld strength, although the reliability of these results was not firmly established because of the small number of specimens (3 or 4) welded in each case.

Work during the current period with further refinements in the equipment has provided additional affirmative results with power-force-programmed welding of molybdenum-0.5% titanium alloy, as well as confirming results previously obtained with Inconel X-750.

A. Power-Force Programming Experiments with Inconel X-750 and Stainless Steel

Earlier in the program (2), welding was carried out with 0.016-inch Inconel X-750 and 0.031-inch Type 304 stainless steel, using four PFP patterns (Figure 1): A involved welding with essentially constant power and force, which is generally representative of standard ultrasonic welding to date; B provided increased clamping force at the beginning of the weld

* Numbers in parentheses refer to references at end of report.

interval; C provided increased force at the beginning and increased power at the end of the interval; and D was essentially the same as C but with lower over-all weld energy.

The data previously presented (2) included statistical analysis of the significance of difference in strength obtained with the various patterns. With both materials there appeared to be differences between A and C, between A and D, and between B and D. On the basis of weld strength, Pattern D seemed most effective.

Inasmuch as the statistical reliability of this work was marginal, due to the limited number of specimens, additional experiments were carried out using Patterns A, C, and D, and with a minimum of seven samples in each group. The data obtained are recorded in Tables I and II, and the results of analysis for significance (according to 3 and 4) are shown in Table III.

With the stainless steel, no significant difference in weld strength was evident among the three groups. A difference had been evident in the earlier experiment, but those data had been obtained from only three or four samples in each group. The present experiment, which involved ten samples per group, is considered more statistically reliable. Consideration will be given to different PFP patterns for this stainless steel.

On the other hand, in the case of Inconel X-750, significant differences between A and C and between A and D were evident, confirming the results previously obtained. C and D were not significantly different. For this material, power-force programming in either Pattern C or Pattern D apparently does indeed have a beneficial effect on weld strength.

B. Preliminary Welding of Molybdenum-0.5% Titanium Alloy

Prior to investigating the effect of power-force programming in welding this material, scouting experiments were carried out to determine an approximate clamping force and the total energy requirement for welding 0.005-inch and 0.010-inch gages of molybdenum-0.5% titanium alloy. Welds were made at clamping forces ranging from 200 to 900 pounds and at several power levels, and were examined visually. When apparently good bonds were obtained, the weldments were tested in tensile-shear. Data obtained with the most favorable welding conditions are presented in Table IV.

On the basis of these data, the 0.005-inch alloy required approximately 500 pounds clamping force and 450-600 watt-seconds of weld energy; the 0.010-inch material required approximately 700 pounds clamping force and a minimum of about 1200 watt-seconds of weld energy. Subsequent power and force programming were based on these values.

C. Welding Molybdenum-0.5% Titanium Alloy with Power-Force Programming

The PFP patterns used for welding the molybdenum-titanium alloy (Figure 2) were essentially the same as those previously used for Inconel X and stainless steel, the major difference being the elimination of the initial low power pulse shown in Figure 1. This had been provided in the earlier patterns because the response of the power programming system was then substantially faster than that of the force programming system. Subsequent modifications to the hydraulic system essentially eliminated this difference in response. In addition, since welding of the molybdenum-titanium alloy had sometimes been accompanied by tip sticking (1), Pattern A was modified to reduce power just before the end of the weld interval, which substantially improved the release of the tip. Another pattern, designated B', was included to evaluate this reduced power effect with Pattern B.

Ten welds were made in 0.010-inch molybdenum-0.5% titanium with each of the five patterns of Figure 2. Eight of each were tested in tensile-shear, and the remaining two were examined metallographically. The PFP values and the results of the strength tests are presented in Table V. As before, the strength data were analyzed statistically to determine the significance of the differences on the 95 percent probability level. The probability calculations are presented in the Appendix, and the results are summarized in Table VI.

From a review of the strength values in Table V, it is apparent that Pattern C produced the strongest welds. Only one value of the eight is below 100 pounds, and the average is about 25 percent higher than those of the other patterns. The somewhat greater total welding energy used for Pattern C might have contributed to the higher strengths, but this seems doubtful.

On a statistical basis (Table VI), the only significant difference is between Patterns A and C. Inasmuch as A represented essentially unprogrammed welding, it appears that power-force programming does indeed make a contribution to welding this material.

Results of metallographic evaluation of weldments from these groups are summarized in Table VII. Although completely crack-free welds were not obtained under the welding conditions used herein, these PFP weldments did not exhibit the gross cracking previously encountered with this molybdenum alloy. The Pattern C welds were the best of the group, confirming the results of the strength tests. Specimen 12-C (Figure 3) showed excellent bonding across the entire interface, although one slight edge crack was noted (Figure 3B).

This experimental work appears to demonstrate that power-force programming facilitates the ultrasonic welding of molybdenum-0.5% titanium alloy. Further work with revised power-force patterns, and particularly with variations of Pattern C, is expected to permit the production of consistently sound, crack-free welds in this material.

D. Future Work

Immediate efforts will be directed to follow-up investigations with the molybdenum-0.5% titanium alloy and extension of PFP welding to heavier gages of this material. The techniques developed will be applied to the niobium alloys and to tungsten.

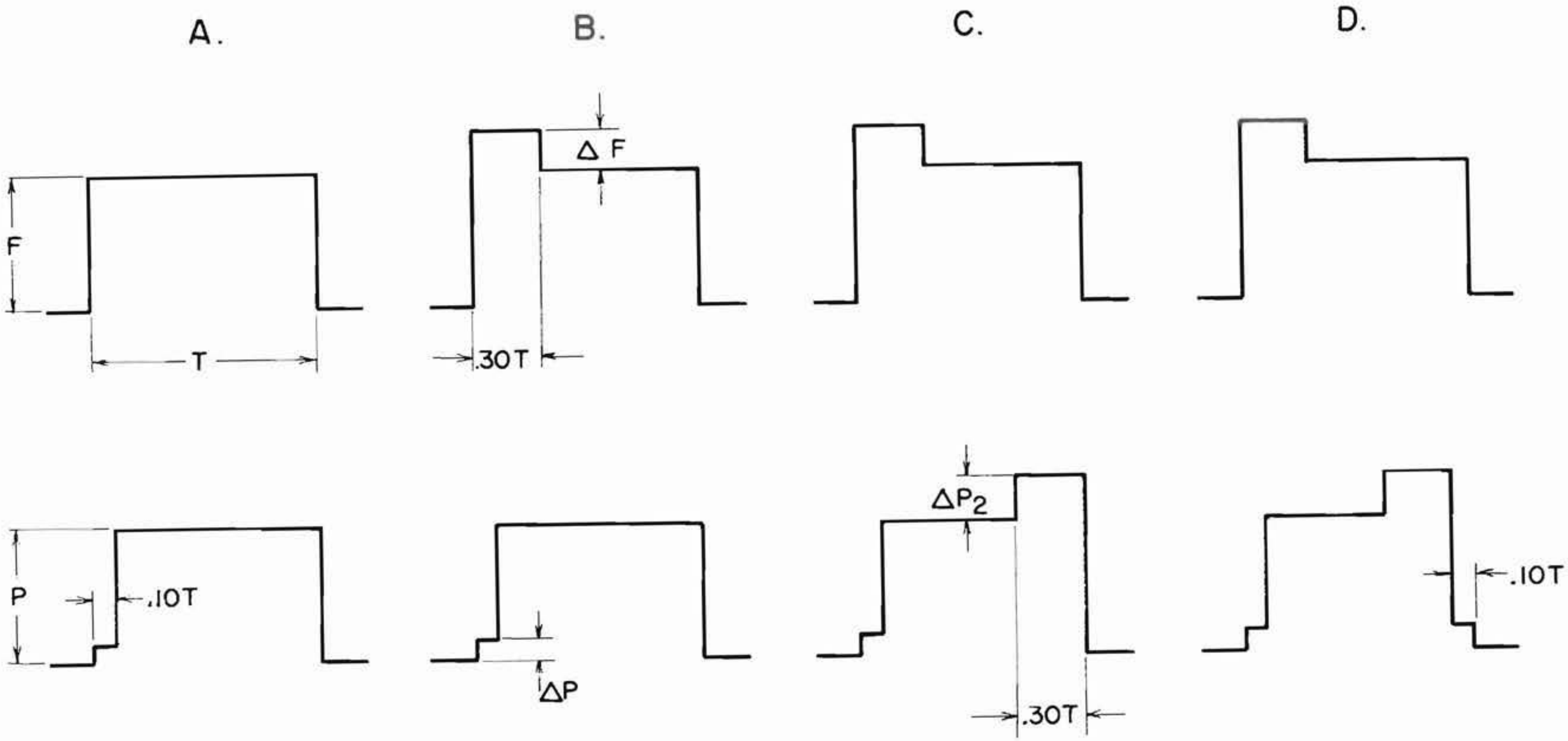


Figure 1

POWER AND FORCE PROGRAMMING PATTERNS AND CORRESPONDING
POWER, FORCE, AND TIME VALUES FOR MATERIALS INVESTIGATED

Material	Gage, inch	Total Weld Interval T, seconds	Clamping Force, pounds		Ultrasonic Power to Transducer, watts		
			F	ΔF	ΔP_1	P	ΔP_2
Type 304 Stainless Steel	0.031	1.0	690	210	150	3100	1000
Inconel X	0.016	1.5	275	105	210	1800	500

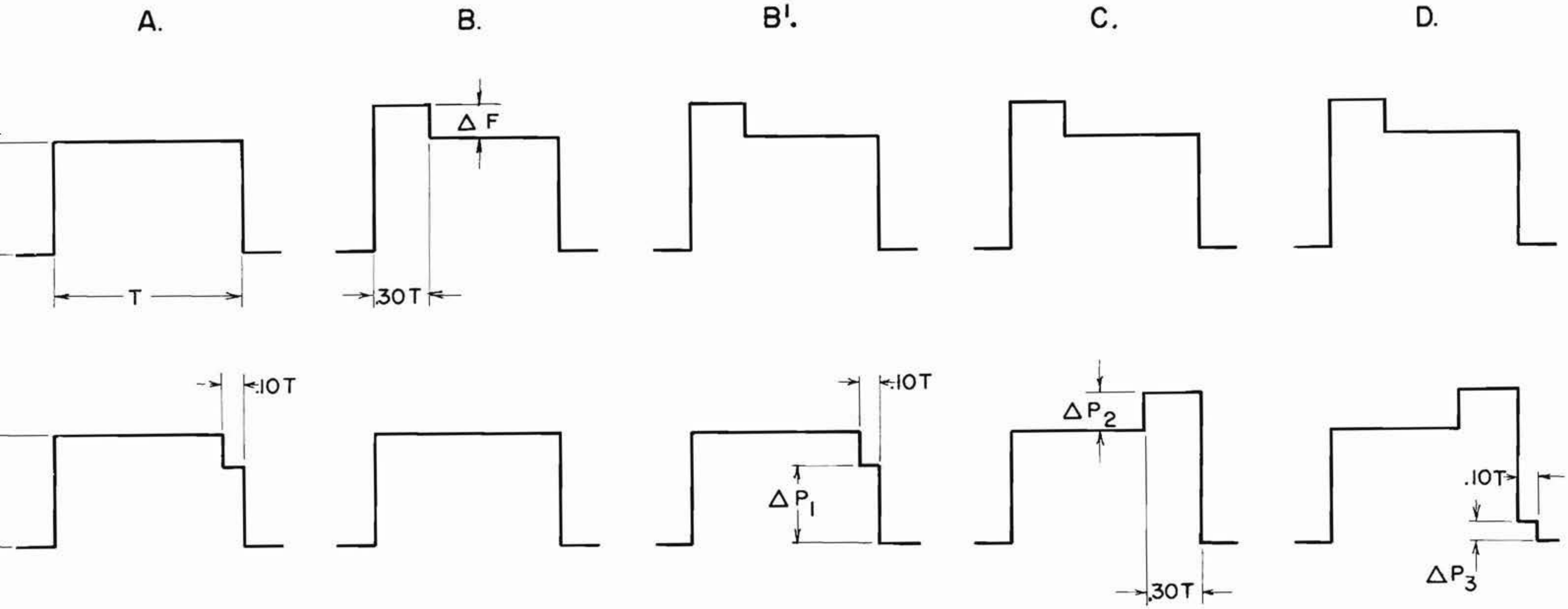
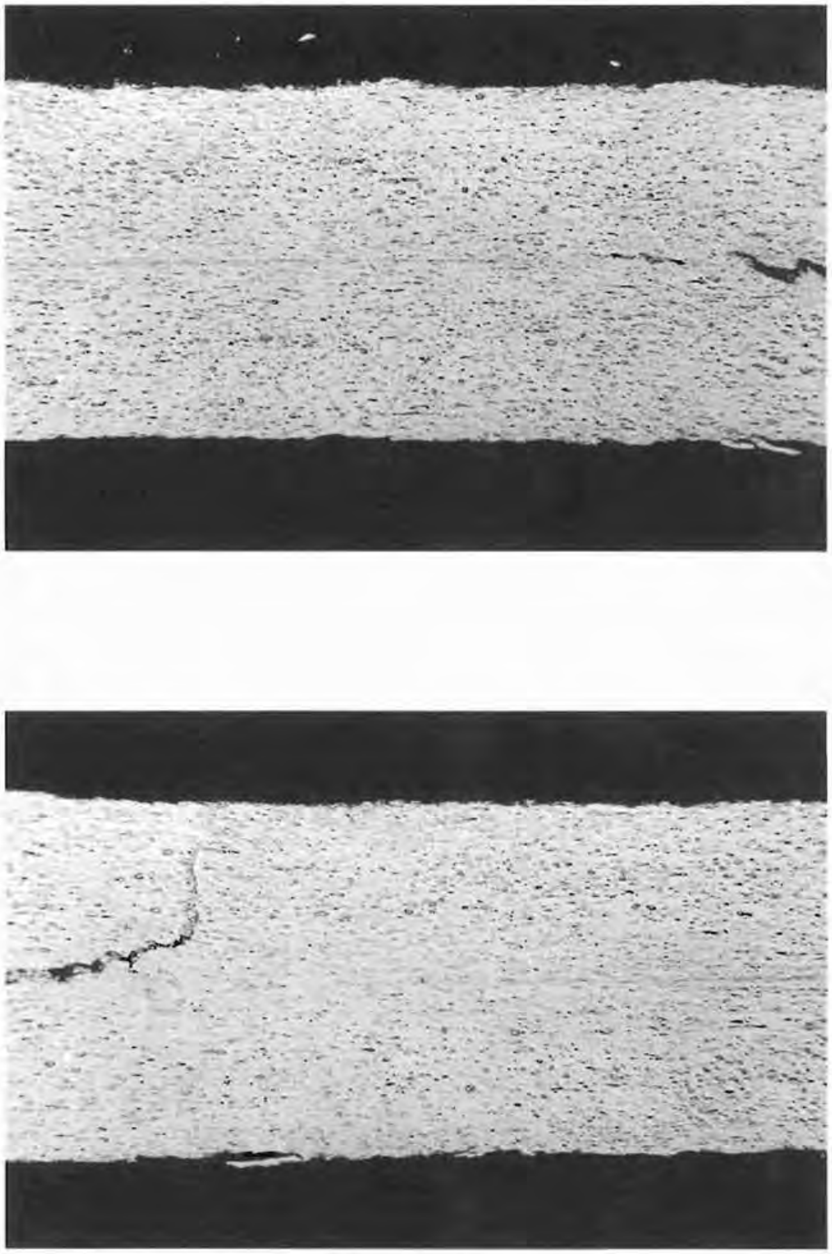


Figure 2

POWER AND FORCE PROGRAMMING PATTERNS FOR WELDING

0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

Material	Gage, inch	Total Weld Interval T, seconds	Clamping Force, pounds		Ultrasonic Power to Transducer, watts			
			F	ΔF	P	ΔP_1	ΔP_2	ΔP_3
Molybdenum-0.5% Titanium	0.010	0.50	700	150	3150	1700	450	200



(A)

(B)

Figure 3

PHOTOMICROGRAPH OF ULTRASONIC WELD
0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY,
SPECIMEN 12-C

(Magnification: 100X)

Table I

EXPERIMENTAL WELDING OF 0.016-INCH INCONEL X-750
WITH POWER-FORCE PROGRAMMING

PFP Pattern (Fig. 1)		Successive Machine Settings			Total Applied Energy, watt-sec	Tensile-Shear Strength, pounds	
		Power, watts	Clamping Force, pounds	Weld Time, sec		Individual Values	Mean
A	Step 1:	210	275	0.10		235 430	
	Step 2:	1800	275	0.90	1640	350 180 355 330 395	325
C	Step 1:	210	380	0.10		435 500	
	Step 2:	1800	380	0.20		505 410	
	Step 3:	1800	275	0.40		500 450	
	Step 4:	2300	275	0.30	1800	395 515 460	463.3
D	Step 1:	210	380	0.10		445 475	
	Step 2:	1800	380	0.20		465 415	
	Step 3:	1800	275	0.30		465 495	
	Step 4:	2300	275	0.30		415 480	
	Step 5:	210	275	0.10	1630		456.9

Table II

EXPERIMENTAL WELDING OF 0.031-INCH TYPE 304 STAINLESS STEEL WITH POWER-FORCE PROGRAMMING

Pattern (Fig. 1)		Successive Machine Settings: Power, watts	Clamping Force, pounds	Weld Time, sec	Total Applied Energy, watt-sec	Tensile-Shear Strength, pounds: Individual Values	Mean
A	Step 1:	150	690	0.10		800	
						1020	
	Step 2:	3100	690	0.90	2800	1040	
						1030	
						1080	
						940	
						1000	
						990	
						1080	
						1070	1005
C	Step 1:	150	900	0.10		1130	
						1120	
	Step 2:	3100	900	0.20		1190	
						970	
	Step 3:	3100	690	0.40		1010	
						940	
	Step 4:	4100	690	0.30	3100	940	
						1240	
						1050	
						1040	1063
D	Step 1:	150	900	0.10		1120	
						1050	
	Step 2:	3100	900	0.20		780	
						1090	
	Step 3:	3100	690	0.30		860	
						980	
	Step 4:	4100	690	0.30		900	
						960	
	Step 5:	150	690	0.10	2800	1040	
						1080	986

Table III

PROBABILITY OF SIGNIFICANT DIFFERENCES IN WELD STRENGTH
OBTAINED WITH VARIOUS POWER-FORCE-PROGRAMMING PATTERNS
(Inconel X and Stainless Steel)

Material	Gage, inch	PFP Pattern (Fig. 1)	Mean μ, pounds	No. of Samples n	Probability of Significance* in Comparison with Pattern A	C
Type 304 Stainless Steel	0.031	A	1005	10	--	
		C	1063	10	>0.6	--
		D	986	10	>0.6	>0.1
Inconel X	0.010	A	325	7	--	
		C	463.3	9	<0.01	--
		D	456.9	8	<0.01	>0.70

* A probability of less than 0.05 shows a significant difference on the 95 percent probability level.

Table IV

PRELIMINARY WELDING OF MOLYBDENUM-0.5% TITANIUM ALLOY

Gage, inch	Power, watts	Clamping Force, pounds	Weld Time, sec	Energy, watt-sec	Shear Strength, pounds	Observations
0.005	600	500	1.0	600	40	
0.005	1500	500	0.3	450	--	Good weld but with excessive tip sticking.
0.010	2200	450	0.25	550	78	Bonding incomplete over weld area.
0.010	3000	450	0.25	750	53	Bonding incomplete over weld area.
0.010	3000	550	0.4	1200	85	Essentially complete bonding over entire weld area.
0.010	3150	700	0.4	1260	90	Complete bonding but with some tip sticking.

Table V

EXPERIMENTAL WELDING OF 0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY
WITH POWER-FORCE PROGRAMMING

PFP Pattern (Fig. 2)	Successive Machine Settings			Total Applied Energy, watt-sec	Tensile-Shear Strength, pounds	
	Power, watts	Clamping Force, pounds	Weld Time, sec		Individual Values	Mean
A	3150	700	0.45		52	
					85	
	1700	700	0.05	1503	100	
					147	
					145	
					126	
					30	
					46	91.4
B	3150	850	0.15		37	
					65	
	3150	700	0.35	1575	62	
					62	
					145	
					147	
					65	
					100	91.1
B'	3150	850	0.15		185	
					83	
	3150	700	0.30		73	
					112	
	1700	700	0.05	1503	70	
					90	
					47	
					33	99
C	3150	850	0.15		74	
					155	
	3150	700	0.20		125	
					137	
	3600	700	0.15	1640	126	
					103	
					143	
					137	125
D	3150	850	0.15		130	
					120	
	3150	700	0.15		92	
					55	
	3600	700	0.15		55	
					141	
	200	700	0.05	1495	64	
					103	95

Table VI

PROBABILITY OF SIGNIFICANT DIFFERENCES IN WELD STRENGTH OBTAINED WITH VARIOUS POWER-FORCE-PROGRAMMING PATTERNS

(0.010-Inch Molybdenum-0.5% Titanium Alloy)

PFP Pattern (Fig. 2)	Mean Strength μ, pounds	No. of Samples n	Probability of Significance* in Comparison with Pattern A	B	B'	C
A	91.4	8	-			
B	91.1	8	>0.9			
B'	99	8	>0.7	>0.6		
C	125	8	<0.02	>0.05	0.2	
D	95	8	>0.8	>0.8	>0.8	>0.05

* A probability of less than 0.05 shows a significant difference on the 95 percent probability level.

Table VII

METALLOGRAPHIC EXAMINATION OF
MOLYBDENUM-0.5% TITANIUM WELDS

PFP Pattern	Specimen No.	Bonding Good	Bonding Fair	Bonding Poor
A	16			X
	31			X
B	11			X
	20			X
	40		X	
	42			X
C	12	X		
	44	X		
D	22	X		
	33	X		

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APPENDIX A

REPRESENTATIVE PROBABILITY CALCULATIONS

The tensile-shear strengths of the welds in Inconel X-750, Type 304 stainless steel, and molybdenum-0.5% titanium alloy, presented in the body of this report, were analyzed statistically to determine if the strength differences obtained with the various PFP patterns were greater than would be expected from random variation alone. Using the significance or "t" test, probability values (P) on the 95 percent confidence level were calculated. When P is less than 0.050, it usually indicates that the difference between two groups is significant and not due to chance.

The following computations were made to compare the data from any two patterns:

$$\bar{D} = y - x$$

$$s = \sqrt{\frac{\Sigma x^2 + \Sigma y^2}{n_1 + n_2 - 2}}$$

$$s\bar{x} = \frac{s}{\sqrt{n}} \qquad s\bar{y} = \frac{s}{\sqrt{n}}$$

$$s\bar{D} = \sqrt{s\bar{x}^2 + s\bar{y}^2}$$

$$t = \frac{\bar{D}}{s\bar{D}}$$

where: x = mean of one group

y = mean of second group

$\bar{D}$ = difference between the means

n_1 = number of samples in one group

n_2 = number of samples in second group

sx = standard deviation of one group

sy = standard deviation of second group

$s\bar{x}$ = $s\bar{y}$ = standard deviation of mean between two groups

$s\bar{D}$ = standard deviation of the difference between means

t = frequency distribution.

The probability value P is determined from the calculated value of "t" and the number of degrees of freedom in the system (number of possibilities minus one). P values are available in tabular form (Ref. 3).

Tables A-I and A-II show these calculations for the molybdenum-0.5% titanium alloy, wherein each PFP pattern was compared with every other pattern. Inspection of the P values in Table A-II reveals one instance in which <P 0.050: the comparison of Patterns A and C. Hence the strength differences obtained with this pattern are statistically significant and do not reflect merely random variation.

Table A-I

STRENGTHS OF RANDOMLY WELDED SPECIMENS OF 0.010-INCH MOLYBDENUM-0.5% TITANIUM

Pattern A

	Shear Strength, pounds	x^2
	52	864.36
	85	40.96
	100	73.96
	147	3,091.36
	145	2,872.96
	126	1,197.16
	30	3,769.96
	46	2,061.16
TOTAL MEAN	91.4	13,972.

Pattern B

	Shear Strength, pounds	y^2
	37	2,926.8
	65	681.2
	62	846.8
	62	846.8
	145	2,905.2
	147	3,124.8
	65	681.2
	100	79.2
TOTAL MEAN	91.1	12,092.

Pattern B'

	Shear Strength, pounds	z^2
	185	7,396
	83	256
	73	676
	112	169
	70	841
	90	81
	47	2,704
	33	4,356
TOTAL MEAN	99	16,479

Table A-I (Concluded)

Pattern C

	Shear Strength, pounds	h^2
	74	2,601
	155	900
	125	0
	137	144
	126	1
	103	484
	143	324
	137	144
TOTAL MEAN	125	4,598

Pattern D

	Shear Strength pounds	i^2
	130	1,225
	120	625
	92	9
	55	1,600
	55	1,600
	141	2,116
	64	961
	103	64
TOTAL MEAN	95	8,200

NOTE that in all cases, $n = 8$.

Table A-II

COMPARISON OF PATTERNS FOR 0.010-INCH MOLYBDENUM-0.5% TITANIUM FROM PROBABILITY CALCULATIONS

Value	PFP Pattern			
	A-B	A-B'	A-C	A-D
$\bar{D}$	0.3	7.6	33.6	3.6
s	$\sqrt{1861.7}$	$\sqrt{2175.1}$	$\sqrt{612.14}$	$\sqrt{1583.7}$
$s\bar{x}^2$	232.7	271.9	76.52	198.0
$s\bar{D}$	21.6	23.32	12.37	19.9
t	0.0138	0.336	2.716	0.18
P	>0.90	>0.70	<0.02	>0.8
	B-B'	B-C	B-D	
$\bar{D}$	7.9	32.9	3.9	
s	$\sqrt{1326.5}$	$\sqrt{1192.1}$	$\sqrt{1449.4}$	
$s\bar{y}^2$	165.8	149.0	181.2	
$s\bar{D}$	18.20	17.26	19.0	
t	0.434	1.906	0.205	
P	>0.6	>0.05	>0.8	
	B'-C	B'-D		
$\bar{D}$	26	4		
s	$\sqrt{1505.5}$	$\sqrt{1762.8}$		
$s\bar{z}^2$	188.2	220.4		
$s\bar{D}$	19.4	21.0		
t	1.340	0.1905		
P	0.2	>0.8		
	C-D			
$\bar{D}$	30			
s	$\sqrt{914.1}$			
$s\bar{h}^2$	114.3			
$s\bar{D}$	15.11			
t	1.985			
P	>0.05			

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